

# Plasma Torch Testing of Hypersonic Vehicle Materials

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**Abstract**—This chapter presents an introduction to ground testing of thermal protection materials used to protect spacecraft and hypersonic vehicles. These test facilities must simulate the aerothermodynamic environments expected during flight. Often these tests have been done in arc-jet facilities. However, inductively coupled plasma torches can generate the relevant test flow field and have advantages. Guidance for using these facilities for thermal protection material performance verification and flight qualification are provided.

## I. INTRODUCTION

For decades government agencies have dominated the access to space and hypersonic flight. In the last decade, multiple private companies have designed, built and launched vehicles into space [1] and many more will succeed in the next decade. A key enabler to space transportation and hypersonic flight is the thermal protection system (TPS) used to protect the vehicle structure from high heating. The hypersonic flight environments are complex and dominated by a shock wave that forms in front of the vehicle and creates a layer of high-temperature chemically reacting gas between the shock and the vehicle. Figure 1 provides a graphic of the physics that affect the heating to the vehicle. [2] The level of heating experienced by the vehicles is dependent on the vehicle shape and flight trajectory, especially the velocity [3], and can range from a few  $\text{W}/\text{cm}^2$  to over a  $1,000 \text{ W}/\text{cm}^2$ . For Apollo [4] the heat fluxes on the blunt heat shield varied from 93 to  $184 \text{ W}/\text{cm}^2$  for entries from low-earth orbit ( $\sim 7 \text{ km}/\text{sec}$ ) and over  $475 \text{ W}/\text{cm}^2$  for Lunar return velocities ( $\sim 11 \text{ km}/\text{sec}$ ). Blunt bodies entering the Martian atmosphere also experience heat fluxes between 100 to  $200 \text{ W}/\text{cm}^2$  on the heat shield [5]. The afterbody experiences heat fluxes below  $10 \text{ W}/\text{cm}^2$ .

The space vehicle designers must account for these environments, select the thermal protection approach and then conduct tests to verify performance and qualify the materials for flight. Ground test facilities that simulate the aerothermodynamic environments of hypersonic flight are required to conduct these tests. Glass [6] provides a good overview of the different approaches to thermal protection, the types of materials used and their application.

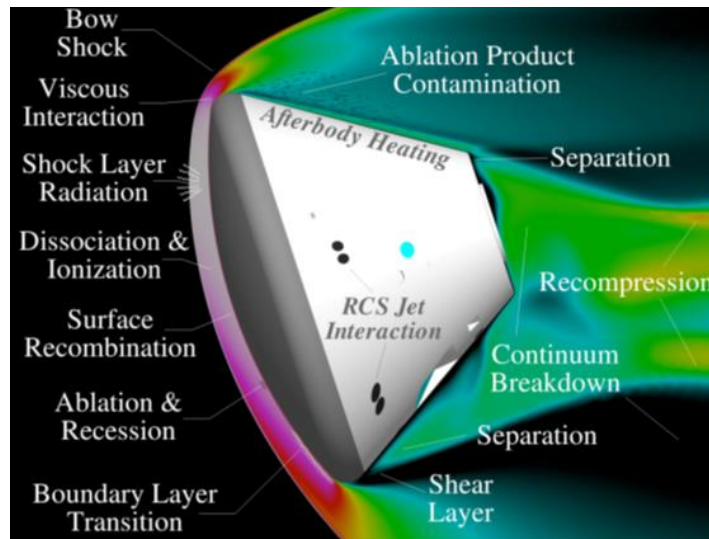


Figure 1- Entry Aerothermal Environment [2].

## II. ARC-JET TESTING

NASA and the US Department of Defense (DoD) have invested in large ground-test facilities at NASA Ames Research Center [7] and Arnold Engineering Development Complex (AEDC) [8] to conduct the thermal protection material tests. These facilities exhaust electrically heated air through nozzles usually into a vacuum chamber and require up to 60 MW of power. The heated air is accelerated through the nozzles to supersonic speeds and form a shock wave around the test articles inserted into the flow field. The high-enthalpy air test environments are similar to that experienced during hypersonic flight. The test facility setup and control parameters can be varied to achieve a large range of heating on a test article. Figure 2 provides an estimate of the heat fluxes achievable in one of the test legs at the NASA Ames Arc-jet Complex. Figure 3 provides a photograph of a test article in the arc-jet flow field.

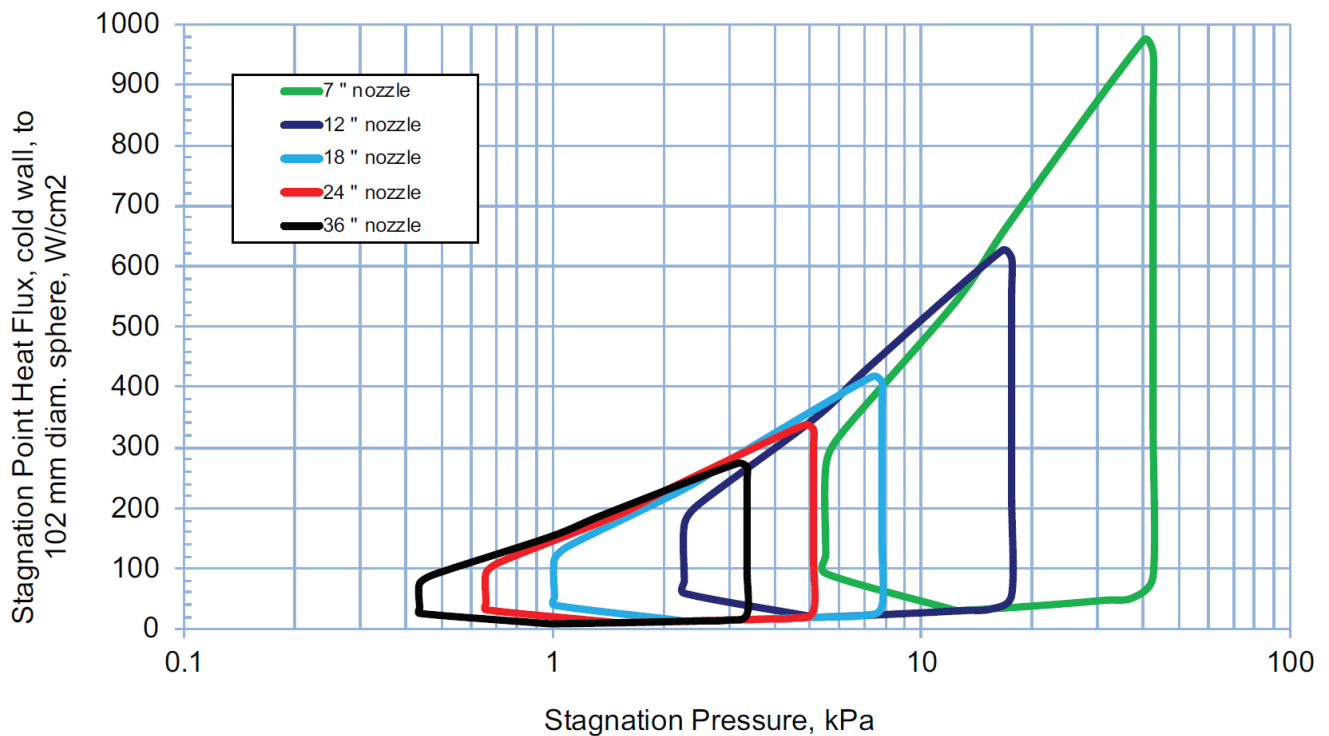


Figure 2 – Test Conditions in NASA Arc-jet Test Leg.

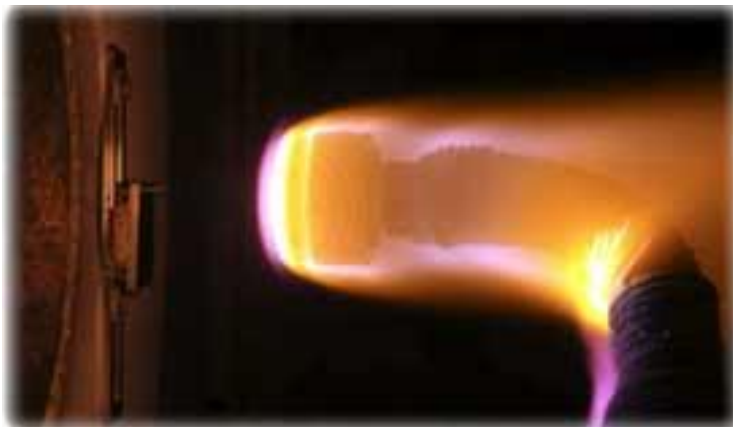


Figure 3 – Stagnation Test Article in Arc-jet Flow field.

The only commercially available arc-jet is the Boeing Large Core Arc-Tunnel (LCAT). Brune [9] provides a description of the LCAT facility and the AEDC facilities. Arc-jets have been the primary test facilities used to develop and certify thermal protection systems for NASA and DoD high-speed vehicles [10]. However, these high-energy facilities require significant infrastructure including power stations, boilers, steam vacuum systems, etc. and can cost hundreds of millions of dollars to build and millions annually to operate. The result is a very high cost for conducting tests with a single test series costing hundreds of thousands of dollars. Additionally, the generation of the high-enthalpy gas with electric arcs results in the gradual erosion of the electrodes, usually copper, which contaminates the flow field and can affect the material response.

### III. INDUCTIVELY COUPLED PLASMA (ICP) TORCH TESTING

Another option for testing TPS materials is the use of inductively coupled plasma (ICP) torches to generate the test conditions. Reed [11] was one of the first to investigate ICP torches as an electrodeless option for testing. The first high power facilities were built in the former Soviet Union in the 1970s-80s [12]. Currently, Russia has a 1 MW and a 100kW torch at the Institute for Problems in Mechanics of the Russian Academy of Sciences [13] and a 1 MW test facility in TsNIIMASH. Greene [14] provides an overview of this test capability. The Von Karman Institute for Fluid Dynamics in Belgium operates 1.2 MW and 15 kW facilities [15]. Germany has a wind tunnel PWK3 and a 375 kW ICP torch in the University of Stuttgart [16]. In the United States, the University of Texas at Austin [17], the University of Vermont [18] and the University of Illinois Urbana-Champaign [19] have setup these facilities and are actively testing high-temperature materials.

#### A. Inductively Coupled Plasma (ICP) Torch Test Setups

An excellent description of the generation of the ICP torch test gas and its stabilization and discharge are provided by Greene [14]. The high-enthalpy test gas can be produced over a range of input voltages and gas flow rates which defines its operational envelope which is unique to each ICP torch. Often the gas is discharged into ambient air resulting in a subsonic flow field to which TPS materials can be exposed for testing. For this case the flow field is relatively steady for several exit-diameters downstream of the chamber exit before the flow breaks down and does not provide steady test conditions. As discussed by Fletcher and Playez [18] and Houghton [20], the subsonic flow field provides a relevant simulation of the stagnation point condition on a hypersonic vehicle especially if the velocity gradient can be modified by geometric scaling of the test article. Another option is to discharge the torch gas into a test chamber held at near vacuum pressures. Depending on the nozzle, the flow field is sonic to supersonic producing a shock wave in front of the test article inserted into the flow. The range of test conditions can be expanded with lower heat fluxes and test pressures achievable. Furthermore, the flow field downstream of the nozzle exit is fairly steady but can have internal shocks depending on the nozzle design.

#### B. Guidance for Material Testing in ICP Torches

As described by Glass [6], several types of thermal protection materials are used in the design of spacecraft, missiles and hypersonic vehicles. Typically, these include ablators, reusable ceramics and carbon-carbon hot structures. During the development and certification of these materials high-enthalpy gas testing is required. Initially, materials are screened to assess the qualitative behavior for a small range of the relevant environments (usually heat flux and pressure). Materials that exhibit minimal changes in geometry and do not crack are desired. For ablators, low levels of recession are expected and acceptable. Those materials that pass initial screening are then exposed to a larger range of environments and the thermal performance of the material is measured. The temperature measurements are used to validate analytical models that are used to design the thermal protection system (TPS) for the space vehicle. Often these data can be obtained on stagnation test articles that vary from 30 mm in diameter for screening to larger than 100 mm for thermal performance measurements. In some cases, the materials are mounted into wedges for testing,

especially to assess their behavior in high-aerodynamic shear levels. If the material is to be used on a leading edge, then small wedge-shaped test articles can be used. Additional testing is needed for specific features on the TPS such as gaps, interfaces or penetrations. These tests often require larger test articles to obtain data on a properly scaled feature. For these cases, stagnation models can be 200 mm or greater in size and for wedge or panel models the test articles can be 200 to 500 mm in size. As mentioned previously, arc-jets have been the work horses for TPS testing and can accommodate a large range of test conditions and test article sizes. However, ICP torches can also provide a relevant environment for testing but, depending on the ICP torch facility size and power, they may be limited to smaller test articles and lower stagnation pressures.

### *C. ICP Torch Environments*

During the early phases of TPS development, materials need to be screened by exposing them to a relevant environment similar to that experienced during hypersonic flight. The key features of this environment are the gas enthalpy, the pressure and the heat flux. The gas enthalpy is an indicator of the energy in the flow and for flight it is primarily defined by the vehicle velocity. The flight stagnation pressure is dependent on the freestream gas density and the vehicle Mach number. With these two parameters, enthalpy and pressure, and knowledge of the vehicle shape and size, stagnation heat fluxes can be estimated. Hiester and Clark [21] provide a relation relating these parameters.

$$h = Cq \sqrt{\frac{R_{eff}}{p_{T2}}}$$

Where  $h$  is the total enthalpy,  $q$  is the stagnation point heat flux,  $R_{eff}$  is the effective radius,  $p_{T2}$  is the stagnation point pressure and  $C$  is a constant depending on the test gas and units [21]. It should be noted that this relation is only valid for supersonic/hypersonic flow since a Newtonian pressure assumption is made to obtain the velocity gradient. To simulate the flight flow conditions for screening TPS materials in a relevant test environment, the test gas enthalpy comparable to that in flight needs to be produced. Enthalpy drives the level of gas dissociation and ionization in the flow field. Figure 4 depicts flight trajectories in Earth's atmosphere and provides an indicator of the altitude/velocity space in which air dissociation and ionization are important to consider. The bulk enthalpy of the test gas is often obtained [22] by computing the total electrical energy and gas flow rate put into the system and then subtracting the energy lost to cooling of the test hardware. The bulk enthalpy compared to the energy input into the system is an indication of the facility efficiency.

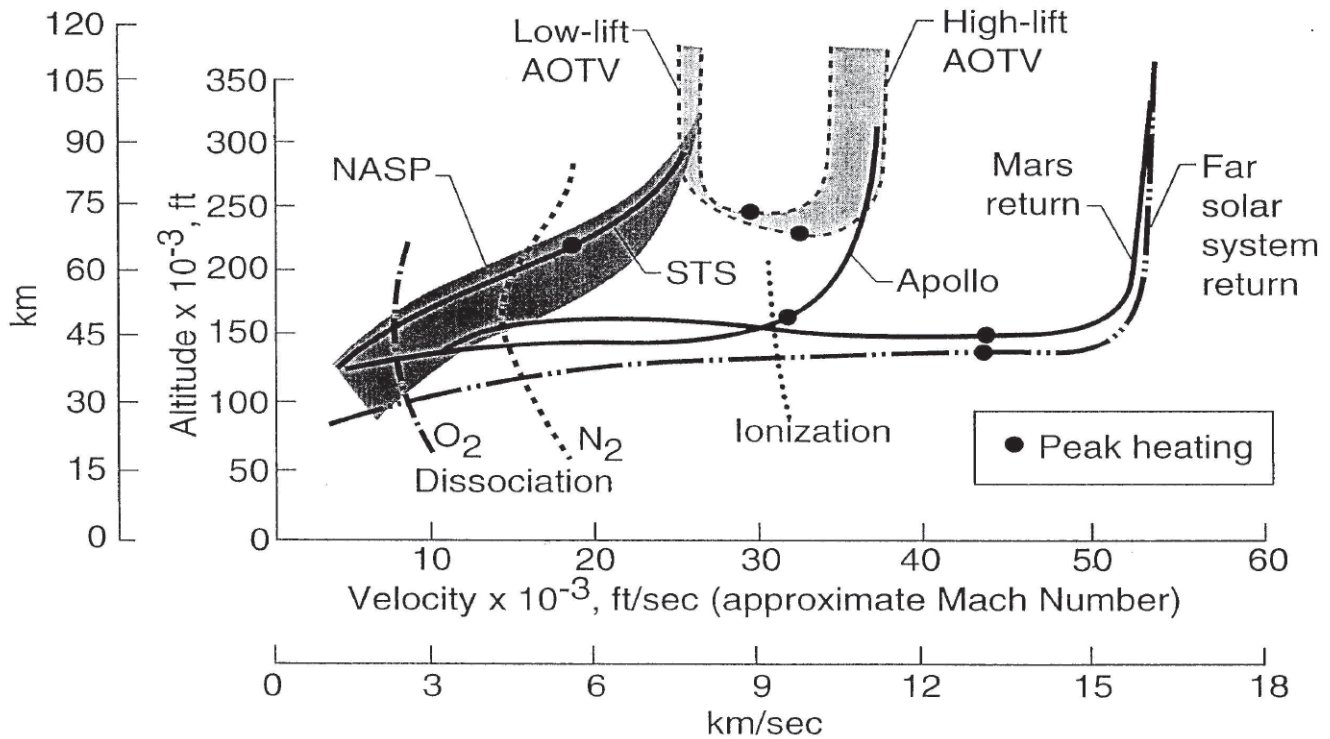


Figure 4 – Hypersonic Flight in Earth's Atmosphere and Air Chemistry State [23].

For a subsonic ICP torch, the test gas is energized by oscillating magnetic fields generating a high enthalpy gas that is ejected into ambient air and forms a flow field comparable to that behind a shock in front of a flight vehicle. The appropriate test gas needs to be selected depending on the end-use – air for hypersonic flight in Earth's atmosphere or carbon-dioxide for entry into a Martian atmosphere.. Low-power ICP torches can generate these environments for material screening at a relatively low cost and with minimal infrastructure. The test articles are small (25 – 30 mm in diameter) and about the same diameter as the ICP chamber exit. The range of test conditions (enthalpy, pressure and heat flux) can be expanded by ejecting the test gas through a nozzle into a vacuum chamber for small test articles. For subsonic flows the shape of the forward face of the test article is less important. However, for supersonic flows the shape effects the heat flux distribution over the face of the test article.

These screening tests provide information about the general response and stability of the candidate materials including surface temperature, mass-loss and recession rates, and char formation for ablators. Also, the propensity for material cracking and intumescence can be evaluated. Some thermal performance can be assessed with internal and back face thermocouples, but these measurements are influenced by the size of the test articles and the heating on the sides of the specimens. In order to obtain better measurements of the thermal performance, the test articles need to be larger – often about 100 mm in diameter. Testing larger models requires larger diameter flow fields and therefore higher gas flow rates. To achieve a comparable gas enthalpy, more power is also needed which can add to the complexity and cost of the test facility.

Characterization of the flow field is important to understand the environment to which the test articles will be exposed. The enthalpy is rarely constant across the stream of gas into which the test article is immersed and is usually higher near the center. To obtain an indication of the enthalpy distribution across the flow field small heat flux probes are often used to measure the radial heat flux distribution. Multiple types of laser diagnostics are available to determine the thermochemical composition of the flow field and compare

it to that in flight [22]. Future plasma torch facilities may combine multiple torches into one mixing chamber to reduce the gradients across the flow field ([24]. In the United States higher pressure and higher power ICP torches are in development by Applied Plasma Technologies [25]. Numerical simulation of the arc-jet and ICP torch flow fields have become more common place and play an important role in understanding the environments to which the materials are exposed and comparing them to those expected for flight [26], [27], [28], [29]

## CONCLUSIONS

Thermal protection materials are used in many locations on vehicles exposed to the high-energy environments associated with hypersonic flight. Before application to a flight vehicle, these materials need to be tested in high-energy ground test facilities. Typically, that testing has been done in arc-jet facilities. However, inductively coupled plasma (ICP) torches can also be used especially in the earlier stages of material development and screening. In the United States, only small research ICP torch facilities currently exist. Broader use of these facilities for material qualification and certification would occur once they are available. The current article also provides some high-level guidelines for using ICP torch facilities for testing thermal protection materials.

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